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Abstract

Background: The integration of extended reality (XR) modalities in medical curricula requires a comprehensive evaluation of pedagogical value, user experience, and institutional sustainability. This study evaluates the technical and experiential variations between virtual reality (VR) full synthetic immersion and mixed reality (MR) holographic transparency frameworks in high-fidelity emergency medical training.

Methods: Utilizing a mixed-methods crossover study design at the Simulation and Interprofessional Development Centre (SIDC), 60 Year 4 undergraduate medical students completed an identical ‘Level 1 and 2 Approach to Bronchial Asthma’ simulation across two distinct configurations: Meta Quest 3 headsets (VR) and Microsoft HoloLens units (MR). Each deployment featured a strict timeline consisting of a 2-minute technical setup followed by 7 minutes of active simulation, separated by a 7-day washout period. Following student tracks, an expert panel of 20 clinical faculty members completed structured evaluative appraisals.

Results: Quantitative evaluation via paired Wilcoxon signed-rank tests revealed that VR consistently and significantly outperformed MR across all ten evaluated dimensions ($p < 0.05$). VR achieved superior scores in ease of use (4.18 vs. 2.72), physical comfort (4.23 vs. 3.40), and perceived learning outcomes (4.30 vs. 3.17). Qualitative thematic analyses confirmed that VR's physical controllers and haptic feedback offered critical interaction precision under pressure, driving an 88.3% student recommendation rate for future curriculum integration. Conversely, the expert panel strongly prioritized the open-boundary format of MR for environmental safety and direct peer communication, exposing a clear generational demographic split where 30.0% of expert educators advocated for MR despite its current gesture-tracking latencies and content constraints.

Conclusion: While VR stands out as the preferred, operationally reliable medium for independent high-fidelity diagnostic mastery, MR preserves essential ambient awareness for multi-user classroom management during medical emergency training.

Keywords: Metaverse, Extended reality (XR), Virtual reality (VR), Mixed reality (MR), Medical education, Clinical simulation, Emergency medicine.

1. Introduction

The paradigm of modern medical education is undergoing a rapid digital transformation, driven by the integration of Extended Reality (XR) architectures. Immersive technologies are increasingly deployed to bridge the traditional gap between classroom theory and high-acuity clinical execution. For instance, recent studies in undergraduate medical education demonstrate that immersive virtual reality (VR) simulations significantly enhance foundational human anatomy training, improve spatial performance, and reduce student exam-related anxiety [1,16]. Building directly upon these findings, advanced implementations have expanded into critical care training; previous research indicates that metaverse-based emergency simulation platforms successfully cultivate clinical decision-making skills and improve procedural accuracy among undergraduate medical cohorts [2,20]. Unlike classical mannequin-based simulations, XR configurations offer highly repeatable, high-fidelity clinical scenarios accessible without intensive logistical constraints or immediate patient safety vulnerabilities.

This research investigates the strategic implementation of XR modalities within the Year 4 undergraduate medical curriculum at the Simulation and Interprofessional Development Centre (SIDC), RAK Medical & Health Sciences University. As students transition toward clinical clerkships, mastering the management of acute medical crises represents a critical competency milestone. Building upon the core anatomical foundations and emergency care frameworks identified in early medical training [1, 2], this paper isolates

and compares two distinct immersive modalities Mixed Reality (MR; utilising the Microsoft HoloLens 2 architecture) and Virtual Reality (VR; utilising the standalone Meta Quest 3 ecosystem). The primary objective is to evaluate their respective impacts on learner cognitive load, anxiety, physical ergonomics, user satisfaction, and interprofessional team communication protocols during a high-fidelity ‘Level 1 and 2 Approach to Bronchial Asthma’ simulation scenario.

Distinct from conventional single-cohort comparative studies, this investigation adopts a comprehensive, dual-stakeholder evaluative framework. It concurrently integrates quantitative and qualitative feedback datasets from undergraduate medical students experiencing the modalities firsthand, alongside the structured evaluative appraisals of metaverse expert clinical faculty. Given that high-fidelity VR and MR configurations have increasingly dominated traditional, less immersive Augmented Reality (AR) frameworks in acute clinical training applications, this study provides a holistic assessment of how these two leading immersive technologies influence clinical skill acquisition, curriculum viability, and institutional strategic evolution within modern medical education ecosystems.

2. Literature review

The widespread adoption of Extended Reality (XR) modalities principally encompassing Virtual Reality (VR) and Mixed Reality (MR) has rapidly transitioned from an experimental pedagogical innovation to a structured, standardized framework within modern medical education [6,17]. These immersive technical architectures are increasingly leveraged as core pedagogical engines designed to bridge the historical disconnect between theoretical medical sciences and high-acuity, practical clinical decision-making. By offering highly repeatable, standardized, and risk-free simulation environments, they allow learners to navigate complex clinical pathways without compromising patient safety [7]. Furthermore, recent systematic reviews confirm that immersive head-mounted display (HMD) interventions significantly accelerate the clinical learning curve, enhance long-term skill retention, and measurably mitigate student performance-related anxiety when compared directly against traditional, static instructional modalities [8].

However, the current educational and technical literature highlights a distinct structural and cognitive divergence between full synthetic immersion (VR) and holographic transparency overlay (MR) environments. Within acute medical training, VR configurations have demonstrated substantial efficacy in isolating high-stakes, time-sensitive clinical decision-making pathways where absolute control over environmental variables is paramount [9,18]. The deliberate incorporation of advanced sensory engagement factors, multi-modal feedback loops, and physical interaction peripherals within these fully simulated spaces has been shown to dramatically optimize learner motivation, situational focus, and procedural confidence [10,19]. Despite these validated affordances, emerging research emphasizes that user interface design,

technical friction, and baseline hardware familiarity remain pivotal determinants of a platform's true pedagogical utility. Therefore, investigators highlight a critical requirement for structured, pre-simulation familiarization phases to prevent extraneous cognitive load from disrupting the acquisition of core clinical competencies [11].

On the other hand, the deployment of Mixed Reality architectures within healthcare education offers alternative pedagogical trade-offs and distinct interactive capabilities. Because MR configurations preserve the user's ambient awareness of the physical environment, they facilitate direct, unmediated visual collaboration and interpersonal communication among team members [12]. This spatial blending of physical and digital assets frequently co-deployed alongside high-fidelity medical mannequins or technical task trainers has proven exceptionally advantageous for complex three-dimensional anatomical orientation, diagnostic reasoning, and localized clinical maneuvers [13]. Yet, comparative studies indicate that MR platforms frequently suffer from distinct engineering constraints, particularly regarding spatial gesture-tracking accuracy (e.g., "air-tapping" latencies) and optical legibility under varying ambient light conditions. When operating under time pressure, these technical limitations can induce premature cognitive fatigue during rapid-intervention clinical tasks [14]. To navigate these systemic deployment challenges, current institutional research stresses the vital importance of formal faculty development initiatives, the meticulous evaluation of instructor workflows, and the systematic capture of dual-stakeholder perspectives including both learners and educators to achieve successful, sustainable curricular integration [15,21].

Despite the accelerating adoption of XR technologies across medical education curricula, there remains a critical gap in direct comparative evidence examining the distinct educational, ergonomic, and communication-related impacts of VR versus MR. Specifically, empirical evaluation within acute emergency simulation scenarios for medical cohorts remains limited, particularly concerning how these competing modalities influence integrated, interprofessional clinical teamwork training.

3. Methods

3.1. Study Design

A comparative dual-stakeholder evaluative framework utilizing a mixed-methods approach to analyze student and faculty experiences across two distinct head-mounted display (HMD) environments during an acute care simulation.

3.2. Study Setting

The Simulation and Interprofessional Development Centre (SIDC) , Metaverse Lab at RAK Medical & Health Sciences University (RAKMHSU).

3.3. Study population

3.3.1. Target Population

Year 4 undergraduate medical students and clinical faculty experts in metaverse simulation workflows at RAK Medical & Health Sciences University (RAKMHSU).

3.3.2. Sampling Type

Convenience Sampling.

3.3.3. Sample Size

Student Cohort: Out of a total historical cohort of 110 Year 4 undergraduate medical students, recruitment initially commenced with 65 students who consented to participate. Over the course of the data collection process, 5 students dropped out due to scheduling conflicts or incomplete experimental sessions. Consequently, the remaining clean data utilized for the final analysis came from a definitive sample size of 60 student participants, representing approximately 54.5% of the eligible student body. This final student sample size solidly aligns with established literature recommendations demonstrating that a cohort size between 10 and 40 participants is statistically sufficient for identifying critical pedagogical trends and detecting usability friction in immersive pilot frameworks. Furthermore, an analyzed sample of 60 comfortably fulfills standard methodological “rule of thumb” guidelines requiring at least 12 participants per intervention arm in crossover pilot designs to ensure administrative feasibility, manage technical device constraints, and mitigate data attrition risks [3,4,5].

Faculty Expert Panel: Following the successful completion of the student experiential feedback collection, the investigation systematically transitioned to its secondary evaluative phase. To capture authoritative pedagogical oversight, the study recruited a dedicated panel of 20 clinical faculty experts. These educators were purposively selected based on their active roles in delivering the university’s institutional Training of Trainers (ToT) sessions. This expert group provided the necessary evaluation to assess the direct impact of the deployed VR and MR architectures on clinical learning outcomes, skill mastery, and the optimization of instructor-led simulation workflows.

3.4. Selection criteria

3.4.1. Student Cohort

Inclusion Criteria	Exclusion Criteria
Active enrollment as a Year 4 undergraduate medical student at RAKMHSU.	Self-reported history of severe vertigo, clinical vestibular disorders, or extreme motion sickness/cybersickness.
Successful completion of the standard institutional Metaverse Lab orientation sessions.	Failure to complete the full crossover experimental protocol or incomplete submission of experiential feedback sessions (resulting in data attrition).
Provision of signed hardcopy informed consent prior to study initiation.	
Ability to participate in all scheduled experimental sessions across both head-mounted display (HMD) environments.	

3.4.2. Faculty Expert Panel

Inclusion Criteria	Exclusion Criteria
Active clinical faculty status at RAKMHSU.	Lack of active engagement or familiarity with the deployed VR and MR architectures used for evaluating clinical learning outcomes and skill mastery.
Active role in delivering the university's institutional Training of Trainers (TOT) sessions for metaverse simulation workflows.	Inability to participate in the evaluative phase due to scheduling conflicts or other constraints.

3.5. Technical Frameworks and Simulation Design

The simulation evaluated a single clinical scenario: 'Level 1& 2 Approach to Bronchial Asthma '. As shown in Figure 1, the infrastructural framework paired two parallel hardware layouts:

- Virtual Reality (VR Tracking): Meta Quest 3 headsets presenting a fully synthetic, fully immersive emergency department environment.
- Mixed Reality (MR Tracking): Microsoft HoloLens units projecting holographic patient assets and biological telemetry overlays directly onto the physical space of the Metaverse Lab.



Fig. 1. Hardware Infrastructure Layout for Parallel Modality Testing in the Metaverse Lab.

3.6. Overview of the scenario

A 36-year-old female patient who suffers from asthma became increasingly short of breath while at work. Her usual inhalers were not able to offer her relief from her symptoms. She has been brought in via ambulance. As illustrated in Figure 2 and 3, the immersive framework simulates this clinical presentation within a high-fidelity environment. Throughout this scenario, the patient's condition will further deteriorate (including development of a tension pneumothorax if following the "hard" pathway).

Learners will need to quickly evaluate the patient and begin appropriate first-line intervention. While gathering data and administering initial treatments, they should also be considering the best medium- and longer-term approaches for this patient.



Fig. 2. Simulation Capture of Resuscitation Room Environment during the Asthma Scenario Using MR.



Fig. 3. Simulation Capture of Resuscitation Room Environment during the Asthma Scenario Using VR.

3.7. Learning Objectives (Easy●; Medium■; Hard◆)

●■◆	Use Airway, Breathing, Circulation, Disability, and Exposure (ABCDE) to assess an acutely unwell patient and understand the importance of reassessment following treatment.
●■◆	Recognize when arterial blood gas sampling is indicated and interpret results correctly.
●■◆	Request appropriate investigations and interpret these in the context of the given patient and presentation.
●■◆	Demonstrate prompt recognition of the severity of acute asthma, in response to acutely abnormal physiology, including the progression from severe to life-threatening acute asthma.
●■◆	Implement appropriate regional or national treatment guidelines (e.g., BTS, NHLBI, etc.) to provide initial management of acute asthma.
●■◆	Escalate to relevant teams appropriately and provide succinct and accurate handover.
■◆	Reassess appropriately and implement further management for acute asthma.
■◆	Plan further management for patient with acute life-threatening asthma, including discussing indications for commencing mechanical ventilation.
●■◆	Communicate effectively with colleagues, including those in different disciplines.
■◆	Use the (AVPU) Alert, Voice, Pain, Unresponsive scale (or GCS or similar scale) to quantify consciousness level and recognize potential for airway compromise in the unconscious patient.

3.8. Procedural Flow and Crossover Protocol

As shown in the following diagram (Figure 4), to maximize hardware capacity and maintain structured experimental control, students were rotated in blocks of five. The study adhered to a rigid, multi-phase operational sequence:

3.8.1. Pre-Study Orientation Phase

Before commencing any practical simulation, all students attended a comprehensive orientation session. This session briefed the participants on the specific immersive hardware (Meta Quest 3 and Microsoft HoloLens), reviewed the medical guidelines for the Asthma Treatment scenario, and explained the overall study objectives and crossover design. As illustrated in Figure 4, to ensure further clarification and structural understanding of the clinical workflow, students received a physical hardcopy guide detailing the precise key actions that participants were expected to complete during the evaluation track. At the conclusion of this orientation, students formally signed the hardcopy informed consent form, and each group of five scheduled their upcoming simulation tracks.

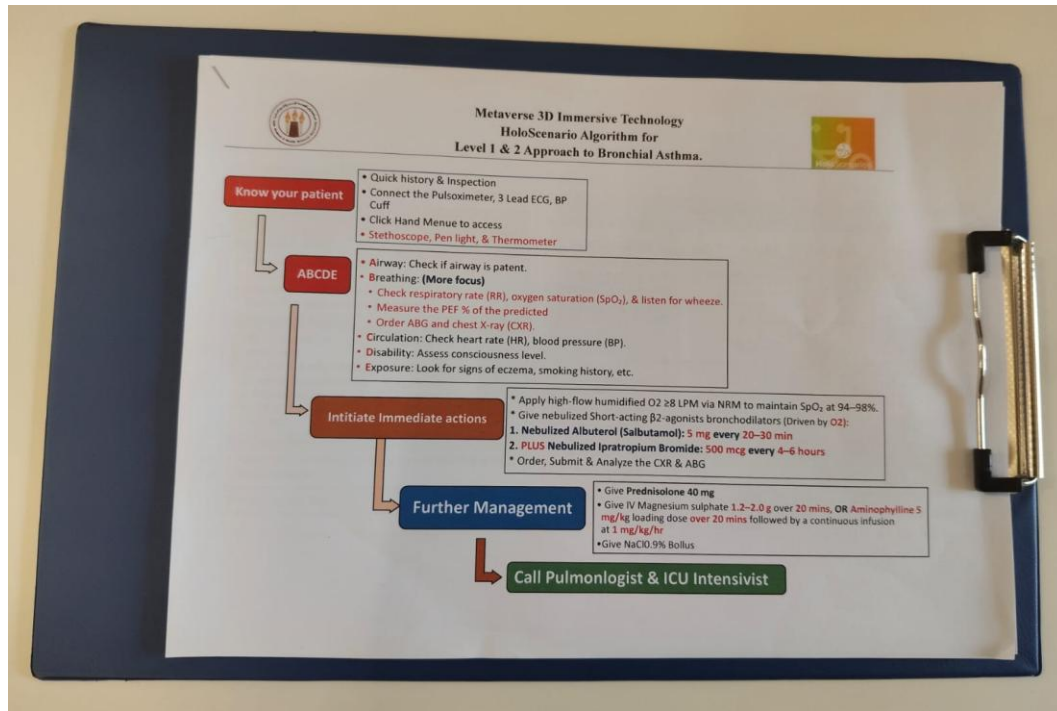


Fig. 4. Hardcopy clinical algorithm handout provided during the pre-study orientation phase.

3.8.2. Cohort Segmentation & Counterbalancing

The 60 participants were split into two parallel tracks of 30 students each. As shown in Figure 5, Group A initiated testing via the Meta Quest 3 Virtual Reality (VR) framework, while Group B simultaneously initiated testing via the Microsoft HoloLens Mixed Reality (MR) platform within the metaverse laboratory environment. This synchronous active session highlights the counterbalanced crossover design in practice; participants on the left and far right operate within the fully enclosed VR environment utilizing physical hand-controllers, while the student cohort in the center utilizes the MR holographic headsets to execute gesture-based diagnostics while maintaining direct visual interaction with their peer team members.



Fig. 5. Live implementation of the counterbalanced crossover simulation tracks within the metaverse lab.

3.8.3. Deployment

Every session was precisely restricted to a 2-minute technical configuration and hardware setup, immediately followed by exactly 7 minutes of active clinical simulation. After each simulation, students spent 3 minutes completing the digital post-session evaluation survey hosted on Microsoft Forms (developed specifically for this study; see Additional file 1 for the MR questionnaire and Additional file 2 for the VR questionnaire). At the conclusion of both crossover tracks, students completed a final comparative preference questionnaire (see Additional file 3).

3.8.4. Washout Phase

A strict 7-day washout period was enforced between treatments to completely dissipate short-term memory, simulator accommodation, and cognitive alignment to the specific event progression.

3.8.5. Cross-Over

After exactly 7 days, the groups swapped hardware platforms: the students who initially used the Meta Quest 3 transitioned to the Microsoft HoloLens, and vice versa. As illustrated in the crossover workflow layout in

Figure 6, they executed the identical 2-minute setup, 7-minute ‘Level 1 and 2 Approach to Bronchial Asthma’ simulation, and terminal evaluations.

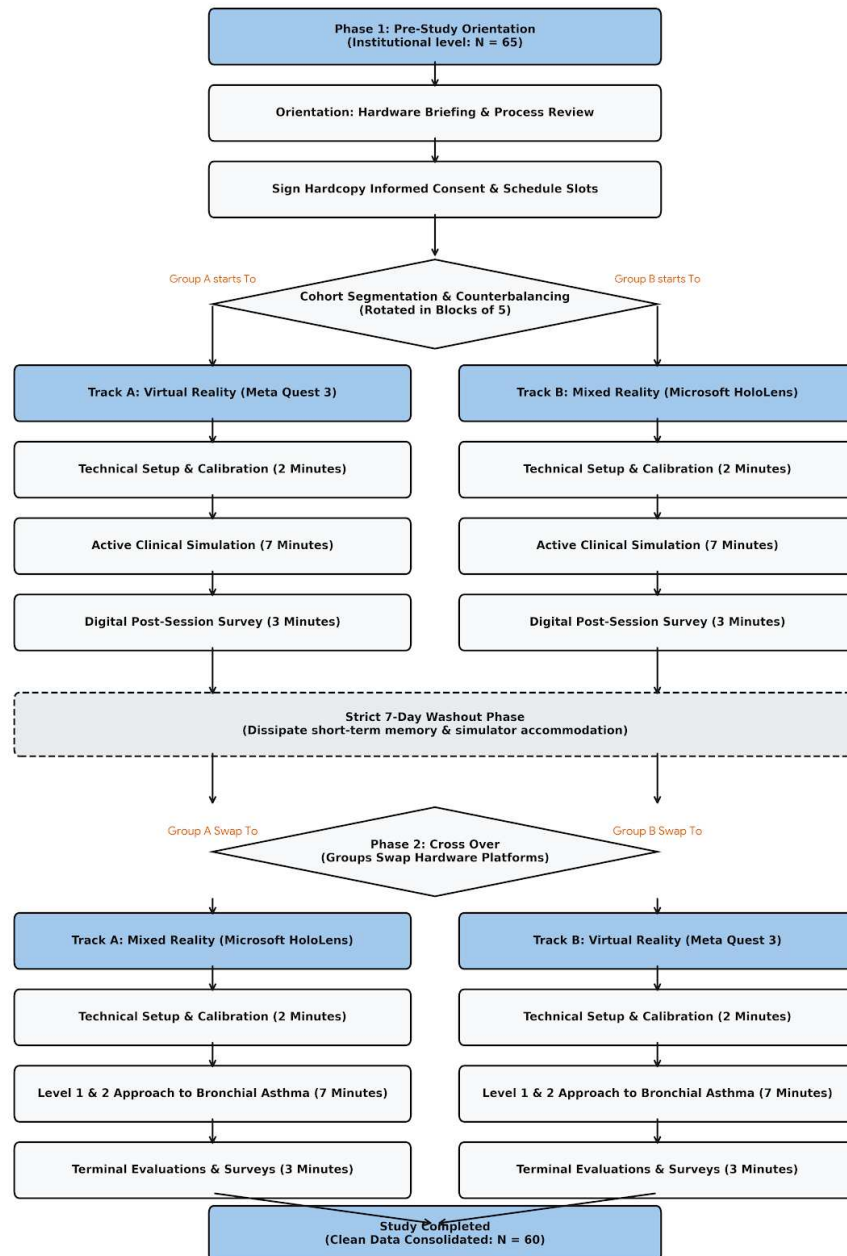


Fig.6. Methodological Flowchart of the Counterbalanced Cross over Design for immersive Simulation Training

4. RESULTS AND ANALYSIS

4.1. Student Quantitative Evaluation of Simulation Modalities

Following their participation in the simulation sessions, students completed structured evaluation questionnaires developed specifically for this investigation (available as Additional files 1, 2, and 3). The questionnaire used a five-point Likert scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree) and assessed three main dimensions: user experience and usability, psychological and cognitive impact, and educational efficacy. The collected responses provide a comparative assessment of usability, physical comfort, cognitive and psychological experience, immersion and realism, learning outcomes, and teamwork and interaction across the MR and VR simulation modalities.

4.2. MR Simulation Evaluation

4.2.1. *Experience & User Usability*

Figure 7 shows the distribution of participant feedback across the four evaluated usability metrics. Positive responses (Agree and Strongly Agree) reached 80% for cybersickness and 65% for physical comfort, compared to 38% for ease of use and 45% for visual clarity. Conversely, negative feedback (Disagree and Strongly Disagree) accounted for 50% in ease of use, 45% in visual clarity, 23% in physical comfort, and 12% in cybersickness. Neutral responses ranged between 8% and 12% across all categories.

Ease of Use: The navigation and interface of the simulation were intuitive and easy to use.

Physical Comfort: I felt physically comfortable throughout the session (e.g., no significant eye strain or dizziness).

Cybersickness: I experienced minimal to no symptoms of cybersickness (e.g., nausea or headache).

Visual Clarity: The text, 3D models, and environment were clear and easy to see.

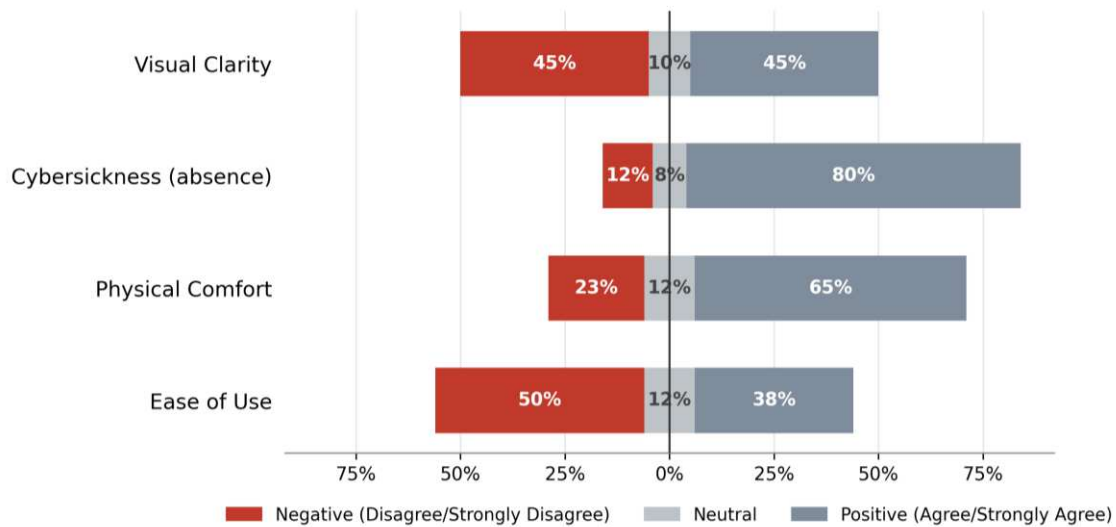


Fig.7.Participant Ratings on MR Simulation Experience and Usability

4.2.2. Psychological & Cognitive Impact

Figure 8 displays participant responses evaluating stress management, cognitive load, and focus & engagement during the simulation. Total positive ratings (Agree and Strongly Agree) accounted for 64% for stress management (52% Agree, 12% Strongly Agree), 54% for cognitive load (40% Agree, 14% Strongly Agree), and 58% for focus & engagement (44% Agree, 14% Strongly Agree). Negative ratings (Disagree and Strongly Disagree) comprised 26% for stress management (18% Disagree, 8% Strongly Disagree), 34% for cognitive load (22% Disagree, 12% Strongly Disagree), and 30% for focus & engagement (20% Disagree, 10% Strongly Disagree).

Stress Management: I was able to manage stress effectively during the clinical scenario.

Cognitive Load: The mental effort required was manageable and did not hinder my learning.

Focus & Engagement: I was able to maintain focus and engagement throughout the session.

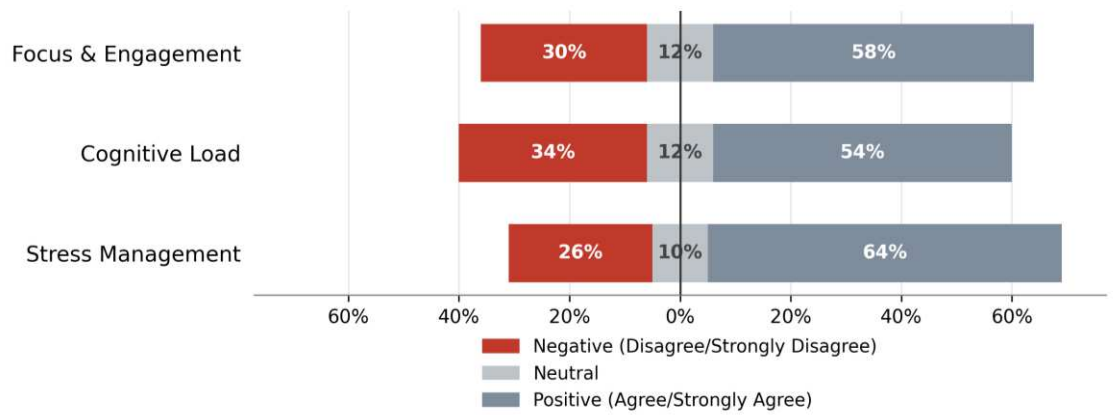


Fig. 8. Participant Ratings on Psychological and Cognitive Impact

4.2.3. Educational Efficacy

Figure 9 presents participant evaluations across immersion & realism, learning outcomes, and teamwork/interaction. Positive responses (Agree and Strongly Agree) reached 74% for immersion & realism (52% Agree, 22% Strongly Agree), 72% for learning outcomes (48% Agree, 24% Strongly Agree), and 66% for teamwork/interaction (42% Agree, 24% Strongly Agree). Negative ratings (Disagree and Strongly Disagree) accounted for 18% in immersion & realism (12% Disagree, 6% Strongly Disagree), 14% in learning outcomes (11% Disagree, 3% Strongly Disagree), and 22% in teamwork/interaction (14% Disagree, 8% Strongly Disagree). Neutral feedback ranged from 8% to 14% across the measures.

Immersion & Realism: The level of immersion and realism was sufficient for medical training.

Learning Outcomes: The simulation was an effective way to learn and practice the clinical skills for this session.

Teamwork/Interaction: The modality supported effective teamwork and interaction with others.

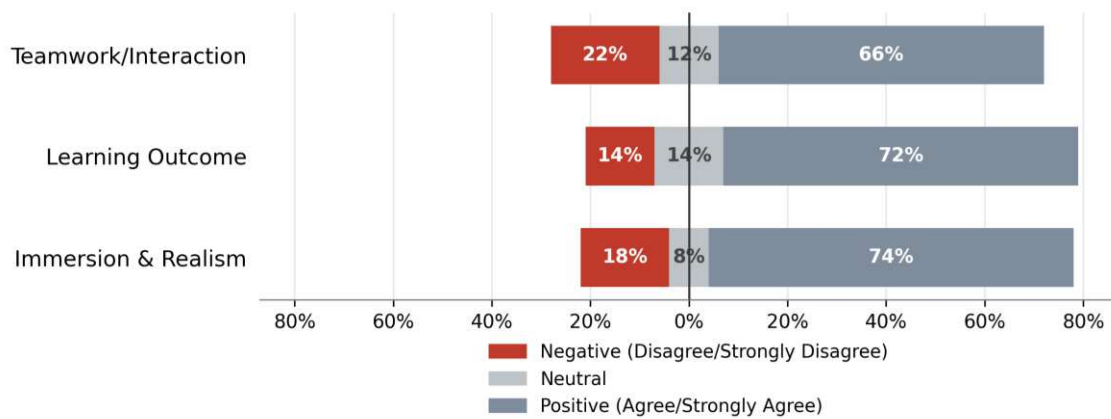


Fig. 9. Participant Ratings on Educational Efficacy

4.3. VR Simulation Evaluation

4.3.1. User Experience & Usability

Figure 10 presents participant ratings across ease of use, physical comfort, cybersickness, and visual clarity. Positive feedback (Agree and Strongly Agree) was consistently high across all four dimensions, reaching 80% for ease of use, physical comfort, and cybersickness, and 77% for visual clarity. Combined negative ratings (Disagree and Strongly Disagree) remained low between 6% and 13%, while neutral responses accounted for 10% to 14%.

Ease of Use: The navigation and interface of the simulation were intuitive and easy to use.

Physical Comfort: I felt physically comfortable throughout the session (e.g., no significant eye strain or dizziness).

Cybersickness: I experienced minimal to no symptoms of cybersickness (e.g., nausea or headache).

Visual Clarity: The text, 3D models, and environment were clear and easy to see.

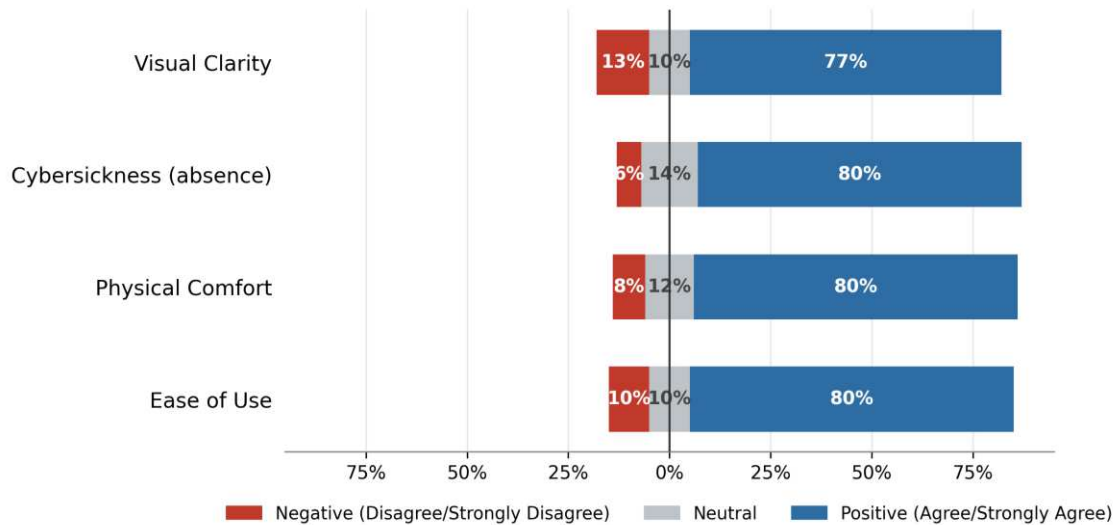


Fig. 10. Participant Ratings on VR Simulation Experience and Usability

4.3.2. Psychological & Cognitive Impact

Figure 11 presents participant ratings for stress management, cognitive load, and focus & engagement. Positive feedback (Agree and Strongly Agree) was consistently high across all dimensions, reaching 82% for stress management (52% Agree, 30% Strongly Agree), 82% for cognitive load (48% Agree, 34% Strongly Agree), and 84% for focus & engagement (44% Agree, 40% Strongly Agree). Combined negative ratings (Disagree and Strongly Disagree) were minimal, accounting for 4% in stress management and 6% in cognitive load, with 0% recorded for focus & engagement. Neutral responses ranged between 12% and 16%.

Stress Management: I was able to manage stress effectively during the clinical scenario.

Cognitive Load: The mental effort required was manageable and did not hinder my learning.

Focus & Engagement: I was able to maintain focus and engagement throughout the session.

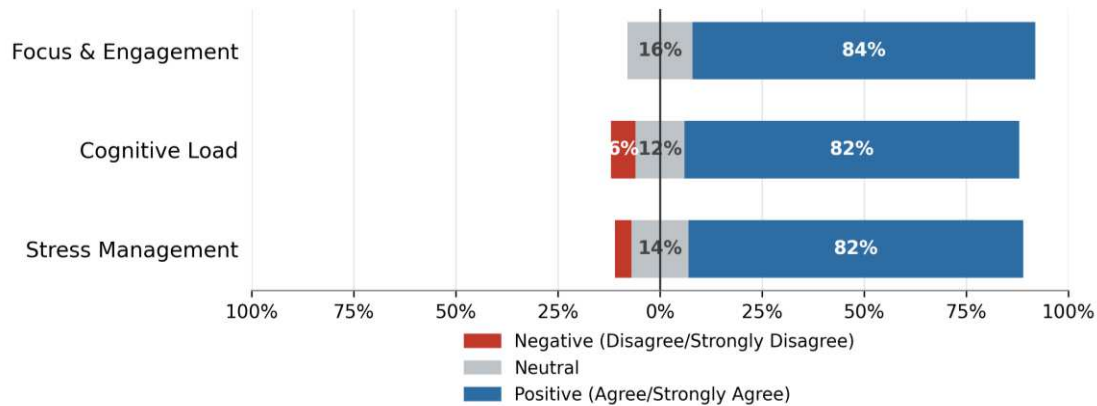


Fig. 11. Participant Ratings on Psychological and Cognitive Impact

4.3.3. Educational Efficacy

Figure 12 displays participant ratings across immersion & realism, learning outcomes, and teamwork/interaction. Positive feedback (Agree and Strongly Agree) remained high across all measures, reaching 63% for immersion & realism (38% Agree, 25% Strongly Agree), 71% for learning outcomes (38% Agree, 33% Strongly Agree), and 60% for teamwork/interaction (31% Agree, 29% Strongly Agree). Combined negative ratings (Disagree and Strongly Disagree) were 12% for immersion & realism, 2% for learning outcomes, and 14% for teamwork/interaction. Neutral responses ranged from 5% to 11%.

Immersion & Realism: The level of immersion and realism was sufficient for medical training.

Learning Outcomes: The simulation was an effective way to learn and practice the clinical skills for this session.

Teamwork/Interaction: The modality supported effective teamwork and interaction with others.

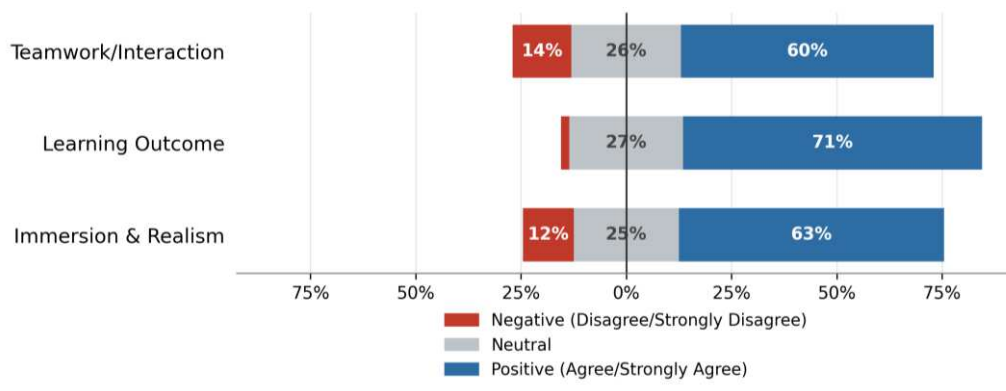


Fig. 12. Participant Ratings on Educational Efficacy

4.4. MR vs VR Simulation Evaluation

To robustly delineate the structural and experiential variances between the two technical frameworks, a non-parametric paired Wilcoxon signed-rank test was performed on the student evaluative metrics (N = 60). The inferential analysis revealed highly significant, systematic performance advantages favoring the fully synthetic Virtual Reality (VR) ecosystem over the Mixed Reality (MR) layout across all ten evaluated dimensions ($p < 0.05$). The complete statistical framework containing calculated mean parameters, medians, Z-values, and explicit significance horizons is systematically compiled in Table 1.

Evaluation dimension	MR mean (median)	VR mean (median)	Z-value	p-value
Ease of use	2.72 (2.0)	4.18 (4.0)	-5.58	< 0.001*
Physical comfort	3.40 (4.0)	4.23 (4.0)	-3.53	< 0.001*
Lack of cybersickness	3.58 (4.0)	4.08 (4.0)	-2.14	0.0327*
Visual clarity	2.95 (3.0)	4.25 (4.0)	-5.21	< 0.001*
Stress management	3.12 (3.0)	3.97 (4.0)	-4.10	< 0.001*
Cognitive load (optimized)	3.37 (4.0)	4.15 (4.0)	-3.87	< 0.001*
Focus & engagement	3.40 (4.0)	4.28 (4.0)	-4.15	< 0.001*
Immersion & realism	2.88 (3.0)	4.17 (4.0)	-5.14	< 0.001*
Perceived learning outcome	3.17 (3.0)	4.30 (4.0)	-5.11	< 0.001*
Teamwork/interaction	3.50 (4.0)	4.05 (4.0)	-2.40	0.0166*

Table 1. Comparative analysis of evaluation dimensions between VR and MR modalities (N = 60).

Scores are based on a 5-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree).

Z- and p-values derived from the paired Wilcoxon signed-rank test. *Statistically significant ($p < 0.05$).

MR: Mixed Reality, VR: Virtual Reality.

Scores are based on a 5-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree).

Z-values and p-values derived from the paired Wilcoxon signed-rank test.

As illustrated in the dimensional bar chart in Figure 13, the quantitative evaluation highlights specific operational patterns divided across three key performance themes:

4.4.1. Usability, Comfort, and Technical Performance

Participants reported significantly lower tracking friction and greater platform access within the fully enclosed VR track. This cohort achieved marked advantages in interface orientation (Ease of Use) and image legibility (Visual Clarity). This visual optimization directly correlated with fewer systemic side effects, rendering significantly lower baseline disorientations (Lack of Cybersickness) and overall superior physical deployment comfort ratings in VR compared to the MR configuration.

4.4.2. Cognitive Load and Psychological Factors

Cognitive demands and situational anxieties were balanced more efficiently within the virtual environment. Students reported advanced context management capabilities (Stress Management) while executing active clinical tracks. Crucially, the interface tracking mechanics yielded a highly optimized Cognitive Load balance, indicating that the system interface did not introduce distracting operational friction during timed emergency tracking.

4.4.3. Pedagogical Engagement and Learning Outcomes

The experiential data exposed clear educational advantages for the VR modality. Driven by a deeply anchored sense of environmental presence (Immersion & Realism), measures of Focus & Engagement were significantly elevated during active tracks. Consequently, students viewed the full isolation environment as a more operationally cohesive medium for clinical skill mastery (Perceived Learning Outcome). This framework also effectively facilitated group tracking workflows, scaling significantly higher for collaborative execution metrics (Teamwork/Interaction).

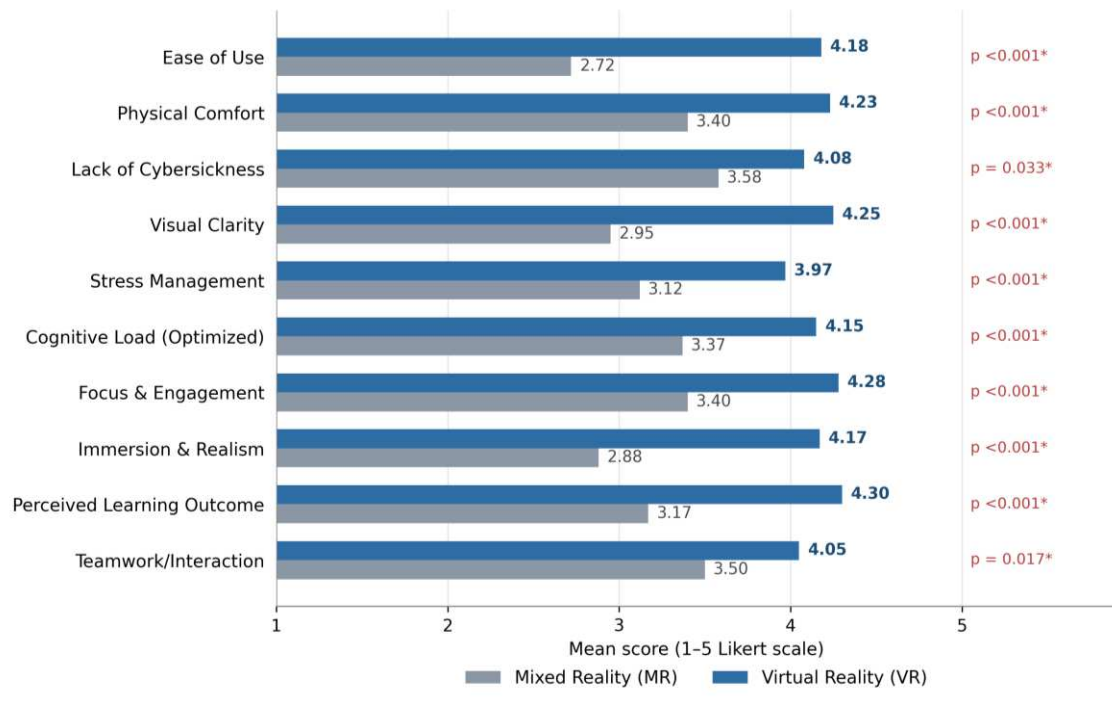


Fig. 13. Comparative Analysis of Student Mean Scores and Statistical Significance Between MR and VR Across Evaluated Dimensions.

Following the completion of both simulation tracks, participants provided a definitive preference recommendation for future integration into the medical curriculum. As shown in Table 2, The descriptive analysis indicated a powerful trend favoring full immersion: 88.3% of the student cohort (n = 53) formally recommended the VR modality for subsequent clinical skills and simulation workflows. Conversely, only 11.7% (n = 7) favored the MR alternative.

Recommended platform	Frequency (n)	Percentage (%)
Virtual Reality (VR)	53	88.3
Mixed Reality (MR)	7	11.7
Total	60	100.0

Table 2. Final platform recommendation for future medical education and training (N = 60).

4.5. Qualitative Evaluation of Student Feedback

To further explore the factors underlying the quantitative results, a thematic analysis was conducted on the open-ended feedback provided by the students at the conclusion of their final sessions. The qualitative data were categorized into four primary themes addressing interaction mechanics, environmental fidelity, visual legibility, and peer collaboration.

4.5.1. Interaction Mechanics and Control Precision

The primary factor distinguishing the two modalities was the user interface design. Students consistently reported that the physical hand-controllers used in the Virtual Reality (VR) framework provided an intuitive, rapid, and reliable method for executing clinical tasks. Conversely, the gesture-based interface of the Mixed Reality (MR) system introduced operational friction during time-sensitive tasks:

Virtual Reality: “The physical controllers made it super easy to interact and choose the medication fast.”
“Using physical controllers in VR made clicking and navigating much faster and more reliable during an emergency.”

Mixed Reality: “Air-tapping gestures are sometimes unresponsive or take too long to detect, which can be frustrating in a timed emergency scenario.”

“The gesture control was a bit laggy and hard to select items under pressure.”

4.5.2. Immersive Realism and Haptic Fidelity

The presence of haptic cues during physical examinations emerged as a critical pedagogical factor. The integration of programmed tactile feedback within the VR framework enhanced the authenticity of the diagnostic process during the acute asthma scenario:

Virtual Reality: “Feeling the patient’s peripheral pulse through the controller vibration was amazing and added real pressure to the scenario.”

“The fully immersive environment felt like a real ER room, and the haptic feedback when taking vitals was highly realistic.”

Mixed Reality: “While seeing the room and my colleagues was great for teamwork, the holographic patient lacks the tactile presence needed for medical training.”

4.5.3. Visual Legibility and Clarity Under Time Constraints

Participants emphasized that the immediate legibility of patient monitors and vital signs is essential when managing a critical clinical case. Resolution limitations and overlay clipping within the MR layout increased cognitive load, whereas the VR display remained consistently clear:

Virtual Reality: “Text labels and monitor charts were very sharp and easy to read instantly.”

Mixed Reality: “The telemetry charts were sometimes hard to read unless you positioned yourself perfectly in front of the hologram.”

“Text and overlay numbers blurred slightly when moving quickly around the environment.”

4.5.4. Group Interaction versus Simulation Presence

Although the MR modality was rated lower for technical interaction, it was valued for maintaining visual contact with the physical surroundings and other team members. However, this benefit was generally secondary to the high clinical immersion provided by the fully virtual environment:

Mixed Reality Support: “MR is great because you don’t lose touch with your team members; you can see their physical expressions clearly.”

Overall Platform Preference Summary: “Even though MR lets you see your classmates, the seamless operation, clear text, and reactive controllers make VR the obvious choice for long-term integration into our curriculum.”

4.6. Quantitative Evaluation of Expert Feedback

To evaluate structural sustainability, academic faculty and clinical training experts provided formal recommendations for curriculum integration (N = 20). As illustrated in Table 3 the descriptive analysis indicated a strong institutional preference for fully immersive systems: 70.0% of the expert panel (n = 14) advocated for Virtual Reality (VR) as the primary training infrastructure. Conversely, 30.0% (n = 6) recommended Mixed Reality (MR), highlighting its distinct capacity for preserving real-world team communication and physical interaction despite its current interface limitations.

Recommended platform	Frequency (n)	Percentage (%)
Virtual Reality (VR)	14	70.0
Mixed Reality (MR)	6	30.0
Total	20	100.0

Table 3. Final platform recommendation for future medical education and training (N = 20).

4.7. Qualitative Evaluation of Expert Feedback

To evaluate institutional viability and curriculum alignment, a thematic analysis was conducted on the qualitative, open-ended feedback provided by the academic faculty and clinical training experts (N = 11) at the conclusion of their evaluation trials. The responses were categorized into four primary themes reflecting technical usability, spatial awareness safety, pedagogical fidelity, and hardware optimization.

4.7.1. Technical Usability and Interface Accessibility

The expert panel highlighted the ease of onboarding as a distinct operational advantage for the Virtual Reality (VR) platform, making it highly suitable for diverse student demographics.

“Pros: Convenient to operate especially for beginners and non-experienced user.”

“Clear and professional and easy.”

“VR provides various scenarios... it can be used for IPE [Interprofessional Education] as well.”

4.7.2. Spatial Awareness and Environmental Safety

A recurring safety concern identified by the experts was the complete visual occlusion inherent to VR headsets. Conversely, Mixed Reality (MR) was praised for maintaining an open boundary that ensures physical safety within the laboratory environment.

“Cons: user may not be safe with physical environment due to closed goggles.”

“The headset is too enclosed making the user unaware of surroundings, prone to bumps or falls.”

“MR is lighter, keeps student engaged but not completely distracted from reality, no vertigo, no boundary.”

4.7.3. Pedagogical Fidelity and Immersion Depth

The clinical experts noted that the depth of presence and situational realism in the VR platform significantly outpaced MR, resulting in superior student engagement and cognitive immersion.

“Realism, Immersion, ease of use, engagement and better team collaboration.”

“In VR different scenarios rather than MR so more educational value and usability. More learning engagement.”

4.7.4. Hardware Ergonomics and Comfort

While VR excelled in software rendering and scenario variety, experts observed that the physical form factor and weight of MR headsets offered notable ergonomic benefits, reducing simulation fatigue and vertigo.

“MR is lighter... no vertigo, no boundary.”

“More clarity, easy to handle.”

5. DISCUSSION

The integration of extended reality (XR) modalities in medical curricula requires a balanced understanding of technical usability, pedagogical value, and user safety. This study evaluated the comparative efficacy of Virtual Reality (VR) and Mixed Reality (MR) simulation frameworks using quantitative data and qualitative feedback from both medical students ($N = 60$) and expert clinical faculty ($N = 20$). Our findings demonstrate a clear and statistically significant preference for the VR simulation framework across nearly all usability and educational metrics. However, the qualitative observations reveal important architectural and demographic trade-offs that institutional decision-makers must consider when incorporating these modalities into medical training programs.

Usability and Technical Infrastructure: Controllers vs. Gestures: A core finding of this study is the significant divergence in technical performance and ease of use between the two simulation modalities. Quantitative metrics showed that the VR modality significantly outperformed MR in Ease of Use (4.18 vs. 2.72, $p < 0.001$) and Visual Clarity (4.25 vs. 2.95, $p < 0.001$). Qualitative data from both students and experts indicate that this difference is primarily rooted in the tracking mechanics of the hardware.

The physical handheld controllers used in the VR system provided immediate tactile feedback and high response accuracy, allowing students to rapidly navigate menus and administer medications under timed pressure. Conversely, the optical, gesture-based (“air-tapping”) interface of the MR headset introduced significant operational friction. Both cohorts noted that the gesture interface was prone to latency or tracking failure when students moved rapidly or worked under stressful emergency constraints. Furthermore, the visual clipping and lower text legibility of holographic overlays in MR increased the users’ cognitive burden, implying that for high-stakes, time-sensitive emergency scenarios, systems utilizing physical tracking accessories remain more stable and reliable than current gesture-only alternatives.

Immersive Fidelity and Learning Efficacy From an educational perspective, the VR framework was perceived as a more potent tool for clinical skill mastery, securing a higher Perceived Learning Outcome mean score (4.30 vs. 3.17, $p < 0.001$). This advantage was heavily driven by Immersion & Realism (4.17 vs. 2.88, $p < 0.001$) and the presence of built-in haptic feedback. Students noted that physical cues, such as controller vibrations mimicking a patient’s peripheral pulse during an acute asthma assessment, added an authentic layer of realism that traditional simulations lack.

In contrast, the MR framework’s holographic patient lacked physical tangibility, reducing the realism of the physical examination. Although MR was valued for allowing students to remain visually connected to their peers, this benefit was generally secondary to the deep clinical isolation and focused presence offered by

the fully closed virtual environment. Consequently, 88.3% of students ($n = 53$) and 70.0% of experts ($n = 14$) recommended the VR system for future curriculum implementation.

Generational Demographics and Institutional Adoption An interesting qualitative pattern emerged during the expert evaluation phase regarding platform preferences. While the overall consensus favored VR, the minority of the faculty panel who recommended MR (30.0%, $n = 6$) belonged predominantly to an older generation of educators. This demographic split suggests that age and prior familiarity with digital interfaces may influence how immersive technologies are perceived and received by faculty.

Older faculty members frequently prioritized environmental awareness, physical safety, and the ability to maintain direct visual contact with students over high-fidelity digital graphics or complex software controls. For these educators, the absolute visual occlusion of VR presented a steeper comfort barrier, whereas MR felt more natural and less disruptive to traditional classroom dynamics. This highlights the necessity of providing targeted training and demographic-sensitive support when introducing XR tools to faculty, as institutional adoption depends heavily on the comfort levels of the educators tasked with delivering the curriculum.

Several limitations must be acknowledged when interpreting these outcomes. First, this evaluation was restricted to a comparison between two specific application setups deployed during the trial, meaning the findings may reflect software-specific engineering and asset optimization rather than the ultimate technical boundaries of the respective hardware architectures. A major confounding factor was the discrepancy in available clinical scenarios; the VR platform offered a more diverse, comprehensive, and mature library of medical cases compared to the more limited content selection available on the MR platform. This imbalance in content depth likely influenced both student and expert perceptions of overall educational efficacy.

Furthermore, the generalizability of these findings is constrained by the specific clinical context of the trial. This comparative analysis was performed entirely within an interactive, high-stakes emergency scenario requiring rapid technical interventions. Consequently, these findings may not apply to other foundational medical domains; in disciplines such as human anatomy education or surgical skills training where spatial mapping, fine motor precision, and real-world instrument manipulation are paramount the structural advantages of Mixed Reality might yield entirely different results.

Additionally, the study relies on subjective, self-reported survey evaluations and perceived milestones rather than objective performance metrics, such as Objective Structured Clinical Examination (OSCE) scores, tracking error rates, or precise time-to-medication delivery.

Finally, while a generational divide was observed qualitatively among evaluating faculty, the study did not formally gather granular demographic data or evaluate age-stratified technology readiness baselines across the evaluator cohorts.

6. CONCLUSION AND FUTURE WORK

This study provides a comprehensive quantitative and qualitative evaluation of Virtual Reality and Mixed Reality simulation frameworks within medical education. Our findings indicate a strong, statistically significant preference for the VR modality among both medical students and expert clinical faculty. Thanks to its physical handheld controllers, mature scenario architecture, and high haptic fidelity, the VR framework offered superior technical usability, lower cognitive friction, and better perceived learning outcomes during high-stakes emergency simulations.

However, the qualitative feedback highlights that selecting an educational technology is not a one-size-fits-all decision. While VR delivers deep narrative immersion, its total visual occlusion presents environmental safety concerns and physical isolation barriers. Conversely, MR preserves real-world environmental awareness and face-to-face peer dynamics advantages that were highly valued by senior faculty members for safe classroom management.

Educational institutions should avoid a uniform approach to XR procurement. Instead, they should adopt a hybrid integration strategy that maps specific clinical learning objectives directly to the unique strengths of each modality deploying VR for independent, high-fidelity diagnostic mastery, and utilizing MR for multi-user, collaborative interprofessional team training.

To expand upon these findings and address the limitations of this study, several avenues for future research are proposed:

- **Objective Performance Metrics:** Future studies should transition from subjective, self-reported survey evaluations to objective milestones. Integrating direct performance data, such as OSCE scores, tracking error rates, and precise time-to-medication metrics, will help quantify the exact clinical accuracy gained from each modality.
- **Biometric and Cognitive Load Analysis:** To deeper understand user strain, upcoming research should incorporate biometric sensors. Utilizing wireless Electroencephalography (EEG) and eye-tracking technologies will allow researchers to objectively map student cognitive load and visual focus under pressure, validating the self-reported stress management scores observed in this study.

- **Expansion Into Other Medical Domains:** Because this study was restricted to a fast-paced emergency scenario, future trials should deploy these platforms across different foundational medical disciplines. Testing both modalities in human anatomy education or technical surgical skill training will help clarify whether MR's spatial mapping and open boundaries yield better results when physical tool manipulation is required.
- **Demographic and Technology Readiness Mapping:** Given the qualitative generational split observed among evaluating faculty, future research should formally gather granular demographic data. Evaluating age-stratified technology readiness baselines will help institutions design better faculty development programs, ensuring smoother institutional adoption of immersive technologies.

Additional Files

- **Additional file 1:** MR Simulation Evaluation Questionnaire (.pdf)

Post-session 5-point Likert scale questionnaire used to evaluate user experience, psychological/cognitive impact, and educational efficacy for the Mixed Reality simulation.

- **Additional file 2:** VR Simulation Evaluation Questionnaire (.pdf)

Post-session 5-point Likert scale questionnaire used to evaluate user experience, psychological/cognitive impact, and educational efficacy for the Virtual Reality simulation.

- **Additional file 3:** Students Evaluation Questionnaire MR vs VR (.pdf)

Terminal crossover evaluation questionnaire assessing overall platform preference and qualitative participant justifications.

Declarations

Ethics approval and consent to participate

This research project received formal ethical approval from the Research Ethics Committee at RAK Medical & Health Sciences University (Approval No. RAKMHSU/RES/HEC/2025-26/145). All procedures and experiments involving human participants were performed in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. All participants provided signed hardcopy informed consent for participation prior to study initiation.

Consent for publication

All participants provided signed hardcopy informed consent prior to study initiation for the publication of their study data. No personal, clinical, or identifying facial features are reported in the accompanying photographic captures.

Availability of data and materials

The survey instruments developed and evaluated in this study are included within this published article and its supplementary information files (Additional files 1, 2, and 3). The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Competing interests

Not applicable

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Not applicable

Authors' contributions

All authors contributed to the study either during its execution or through reviewing this work.

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Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [StudentsEvaluationQuestionnaireMRGigXRvsVRSimX.pdf](#)
- [VRSimulationEvaluation.pdf](#)